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MAGNETIC TAPE UNDULATORS[a]

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ABSTRACT

Magnetic undulators and wigglers are an essential part of most Free Electron Lasers. An interesting possibility is to make short period undulators (microundulators) out of suitably recorded magnetic tapes. Field calculation and measurements on such microundulators are reported.

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I-INTRODUCTION.

A novel application of magnetic recording is discussed, namely, the use of a magnetically recorded medium as an undulator for a free electron laser (FEL). This promises to be an important application since FELs have the potential of becoming unique continuously tunable sources of intense coherent radiation[1].

The FEL radiation is produced when a relativistic electron beam wiggles through a periodic magnetic structure called undulator. If L_0 is the period of the undulator and B the peak magnetic field, the undulator strength is characterized by the parameter $K=eBL_0/2\pi mc$. The electrons emit stimulated sincrotron radiation at a wavelength[2] $L=L_0(1+K^2/2)/2\gamma^2$, when their energy is γmc^2.

In September 1985 the FEL of the University of California at Santa Barbara (UCSB) started operation producing radiation with a wavelength in the vicinity of 400 μm [3]. The energy of the electrons was 3 MeV and the undulator consisted of 1280 Samarium-Cobalt magnets arranged in the Halbach[4] configuration with a 3.6 cm period. The recent upgrade in energy to 6 MeV will allow the production of radiation down to 110 μm. However, as was recognized in a National Academy of Science report[5], it would be desirable to have intense radiation sources down to 25 μm. In order to reach such wavelengths with 3 MeV electrons the undulator period has to be 2.5 mm. It is practically impossible to make such microundulators arranging four individual magnets per period as in the conventional Halbach[4] configuration. An interesting possibility is to use as undulator a periodically recorded magnetic tape.

II. MAGNETICALLY RECORDED UNDULATORS

An analysis of the fields of magnetically recorded undulators will be presented in this section.

A. SINGLE TAPE UNDULATOR. Let us consider a strip of magnetized material of thickness t and width w. The upper surface coincides with the xz plane, with z along the longitudinal axis. The magnetization is

$$\vec{M}=M_0(\hat{z}\cos\theta+\hat{y}\sin\theta)\sin 2\pi z/L_0$$
$$[H(-y)-H(-y-t)]\,[H(x+w/2)+H(x-w/2)], \qquad (1)$$

where H(x) is the Heaviside function (1 for x>0, 0 for x<0), and θ is the angle between the magnetization and the z axis. The magnetic induction field $\vec{B}$ can be obtained from a potential as $B=-u_0\,P$ where the potential is a solution of Poisson equation $\nabla^2 P=-S$. The magnetic source $S=-\vec{\nabla}.\vec{M}$ can be written as

$$S=(M_0/2\pi^2)\sin kz\int_0^{\infty}(dq/q)\int_{-\infty}^{\infty}dp\, F(p,q) \quad , \qquad (2)$$

where $k=2\pi/L_0$ and

$$F(p,q)=[\sin q(x+w/2)-\sin q(x-w/2)]e^{-ipy}$$
$$[1-e^{-ipt}][\sin\theta \sin kz-ik\cos\theta\cos kz/(p-i\varepsilon)] \qquad (3)$$

The magnetic potential, solution of Poisson equation, is given by

$$P=-(M_0/2\pi^2)\int_0^{\infty}(dq/q)\int_{-\infty}^{\infty}dpF(p,q)/(p^2+q^2+k^2) \, . \qquad (4)$$

After integrating in p,q we get the potential which in turn yields the field components

$$B_y=(\mu_0 M_0/2)e^{-ky}(1-e^{-kt})\sin(kz-\theta)W \quad , \qquad (5)$$

$$B_z=(\mu_0 M_0/2)e^{-ky}(1-e^{-kt})\cos(kz-\theta)W \quad , \qquad (6)$$

with the finite width correcting factor

$$W=1-(2/\pi ky)\{\exp[-k(x+w/2)^2/2y]+\exp[-k(x-w/2)^2/2y]\}. \qquad (7)$$

The peak field is independent of the angle .

B. TWO TAPES. CONSTANT MAGNETIZATION ANGLE. In a good undulator $B_z=0$ along the ideal electron trajectory. This can be accomplished with two parallel strips separated by a gap g. If the magnetizations in the upper (lower) strips $\vec{M}_1$ ($\vec{M}_2$) are given by

$$\vec{M}_1=M_0(\hat{z}\cos\theta_1+\hat{y}\sin\theta_1)\sin kz[H(y-g/2-H(y-t-g/2)],$$

$$M_2=M_0(z\cos{}_2+y\sin{}_2)\sin(kz+c)$$
$$[H(-y-g/2)-H(-y-t-g/2) \quad , \qquad (8)$$

the magnetic induction components turn out to be

$$B_y=M_0e^{-kg/2}(1-e^{-kt})\cosh ky\cos(kz-\theta)W \quad ,$$

$$B_z=-M_0e^{-kg/2}(1-e^{-kt})\sinh ky\sin(kz-\theta)W \quad , \qquad (9)$$

where, in order to have $B_z=0$ at $y=0$, we have taken $c=0$ and $\theta_1=\theta_2=\theta$. An undulator can be made with two strips magnetized with in plane recording ($\theta=0$) or vertical recording ($\theta=\pi/2$).

C. ROTATING MAGNETIZATION. This magnetization pattern was first discussed by Mallinson[6] in relation with magnetic recording and by K.Halbach[4] in the context of multipole focussing magnets. For uniformly rotating magnetization the field vanishes on one side of the strip while on the other side it is double than for non-rotating cases. Taking the magnetizations in the upper and lower strips respectively as

$$\vec{M}^r{}_1=M_0[\hat{z}\cos(\eta\mp kz)+\hat{y}\sin(\eta\mp kz)]\,[H(y-g/2)-H(y-t-g/2)]\quad,$$

$$\vec{M}^r{}_2=M_0[\hat{z}\cos(\pm kz)+\hat{y}\sin(\pm kz)]\,[H(-y-g/2)-H(-y-t-g/2)]\quad,\tag{10}$$

the potential inside the gap, turns out to be

$$P^r=-M_0/2(1\pm 1)e^{-kg/2}(1-e^{-kt})\,[\sin(\eta\mp kz)(e^{ky})\mp\sin kze^{-ky}]\ .\tag{11}$$

As we can see from eqs.(10) and (11) we have to choose an appropriate sense of rotation in order to have nonvanishing fields inside the gap. That rotation corresponds to the upper sign in these equations and is as follows: as we move in the positive z direction the magnetization has to rotate clockwise in the upper strip and anticlockwise in the lower. Besides, choosing the phase $\eta=\pi$ in order to cancel B_z at the midplane, we have

$$P^r=-(2M_0/k)e^{-kg/2}(1-e^{-kt})\sin kz \sinh ky \quad , \quad (12)$$

which is double the potential for strips with non-rotating magnetization.

III. MEASUREMENTS

In order to demonstrate the feasibility of using recorded materials as undulators, R.M.White[7] magnetized a 10 mil thick strip of the alloy Fe-28 Cr-10.5 Co. The material has a remanence of 9300 Gauss and a coercivity of 360 Oersted. The sample was recorded with a period of 1.4 mm. This was confirmed decorating the surface with a drop of ferrofluid.

The periodically recorded strip was made available to the FEL group at UCSB. The magnetic field was measured with a probe consisting of ten loops of sides a=0.5 mm by b=10 mm. The probe was dragged along the magnetized strip at a speed of v=1.42 cm/sec. This was achieved by mounting the strip on a milling machine while the probe was held by the chuck and laid flat on the surface of the strip. The voltage signal was amplified with an Ithaco pre-amplifier and with a 465B Tektronix oscilloscope and then send to a Nicolet storage scope. The data was recorded with a plotter.

If the component of the magnetic induction perpendicular to the strip surface is $B=B_0 \sin kvt$ then, the electromotive force generated in the probe is given by $V=2B_0 bv \sin ka \sin(kz-A)$, where $A=\arctan[\mathrm{cosec}\ ka-\mathrm{cotan}\ ka]$. In this way we obtained B shown in the graph as a function of z.

A good magnetic undulator should produce fields of at least a few hundred Gauss. This is clearly not the case of the strip we have analyzed with a period $L_0=1.4$ mm and a peak field of ~ 8 Gauss. However, as the graph also shows, it is possible to record strips with the sine-like magnetizations needed for undulators.

It does seem, from our measurements, that the recording process did not saturate the magnetic material in the strip which, moreover, is rather thin. In order to accommodate the electron beam and produce fields of a few hundred Gauss, a realistic undulator would consist of two strips with period and gap $L_0 \sim g \sim 3$ mm and thickness $t \sim 1$ mm. This leads us to the idea of scaled up magnetic recording techniques[8] with larger recording media and heads.

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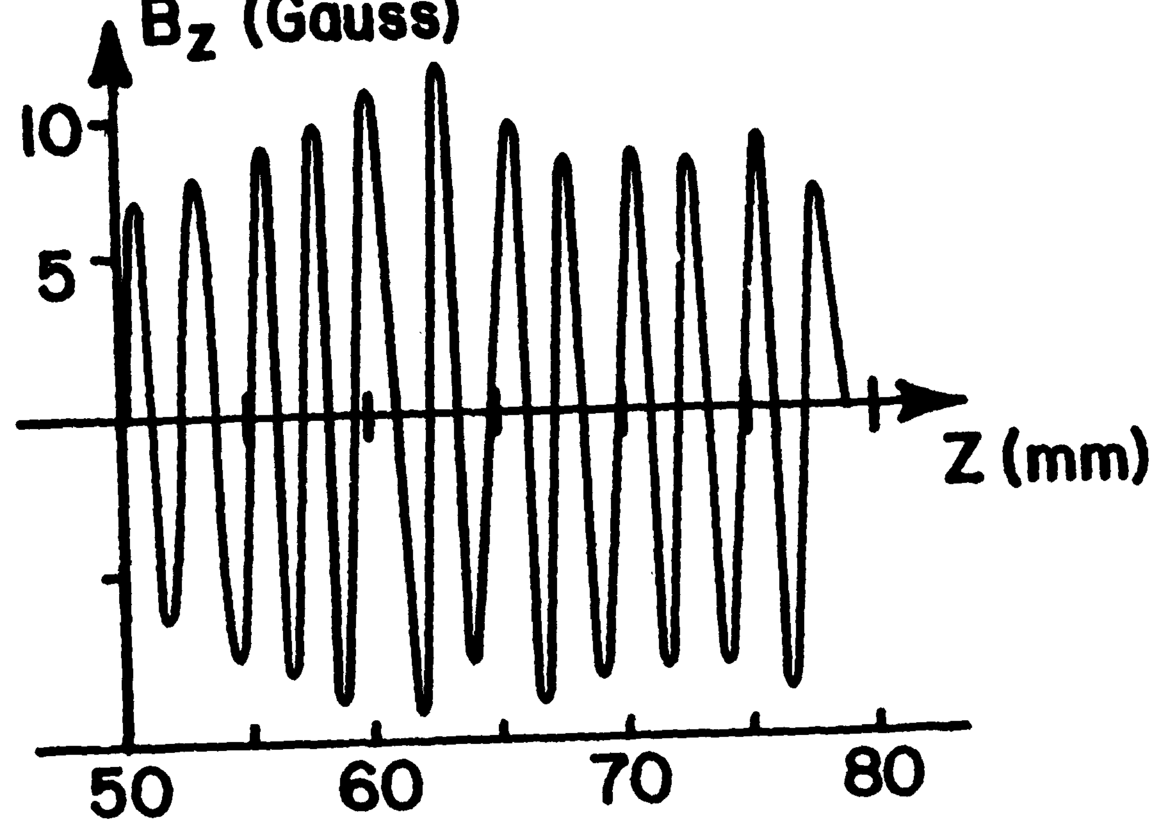
FIGURE CAPTION

Fig. 1. Normal component of B measured at the strip surface.


B_Z (Gauss)
10
5
Z (mm)
50
60
70
80